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Review

Technological avenues and market mechanisms to accelerate methane and nitrous oxide emissions reductions

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SUMMARY

Strategies targeting methane (CH_4) and nitrous oxide (N_2O) emissions are critical to meeting global climate targets. Existing literature estimates the emissions of these gases from specific sectors, but this knowledge must be synthesized to prioritize and incentivize CH_4 and N_2O mitigation. Accordingly, we review emissions sources and mitigation strategies in all key sectors (fuel extraction and combustion, landfilling, agriculture, wastewater treatment, and chemical industry) and the role of carbon markets in reducing emissions. The most accessible reduction opportunities are in the hydrocarbon extraction and waste sectors, where half (>3 Gt-CO_2e/year) of the emissions in these sectors could be mitigated at no net cost. In total, 60% of CH_4 emissions can be mitigated at less than \$50/t-CO_2. Expanding the scope of carbon markets to include these emissions could provide cost-effective decarbonization through 2050. We provide recommendations for carbon markets to improve emissions reductions and set prices to appropriately incentivize mitigation.

INTRODUCTION

Global greenhouse gas (GHG) emissions from anthropogenic activities have continued to increase since pre-industrial levels and have caused a rise in global average surface temperatures of 1.3°C.[1] Mitigation efforts have focused primarily on reducing carbon dioxide (CO_2) emissions because the amount of CO_2 emissions exceeds the amount of other GHG emissions (Table 1). Nonetheless, it is critical to address non-CO_2 GHG emissions because of their important and unique[2] role in global warming. Key non-CO_2 GHGs are methane (CH_4) and nitrous oxide (N_2O). The influence CH_4 and N_2O have on the climate is typically assessed by accounting for their warming impact relative to an equal mass of CO_2. There are different metrics that quantify this equivalency, considering radiative forcing or surface temperature change as drivers.[3] Common metrics are the Global Warming Potential with a 20-year time horizon (GWP_{20}) and a 100-year time horizon (GWP_{100}). In this context, non-CO_2 GHG emissions are typically reported as CO_2-equivalent (CO_2e) emissions using their corresponding GWPs. For CH_4, the Intergovernmental Panel on Climate Change (IPCC) reports in the Sixth Assessment Report (AR6) a GWP_{20} of 79.7 and 82.5 for non-fossil and fossil sources, respectively. GWP_{100} values for non-fossil and fossil CH_4 are 27 and 29.8, respectively. For N_2O, the reported GWP_{20} and GWP_{100} is 273 (Table 1). Such figures highlight the significantly higher warming potentials of these GHGs in comparison to CO_2[2]. While N_2O emissions have contributed less to warming, they have a longer atmospheric lifetime (109 years) than CH_4 (11.8 years) and therefore pose a long-term threat to climate change mitigation efforts (IPCC, 2021a). Overall, it is currently estimated that emissions of these two gases have caused a cumulative warming of 0.65°C.[4]

Figure 1 provides an overview of the major sources of CH_4 and N_2O.[5] Enteric fermentation from cattle in the agricultural sector and fugitive emissions from the oil and gas sector are about half of CH_4 emissions. Managed soils and pastures are the predominant source of N_2O emissions.

Despite the importance of CH_4 and N_2O in anthropogenic global warming, technological and policy interventions mostly center on CO_2 mitigation. For instance, recent market incentives in the United States[7] and China[8] prioritize CO_2 reduction. Similarly, the 45Q tax credit in the U.S. does not consider CH_4 emissions. Stringent reductions in CH_4 and N_2O emissions are needed to meet the Paris Climate Agreement targets.

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Table 1. Global GHG emissions in 2019, 20- and 100-year Global Warming Potentials (GWP_{20} and GWP_{100}) for CO_2, CH_4, and N_2O

	Emissions, 2019 (Gt)[a]	GWP_{20}[b]	GWP_{100}[b]	Emissions in terms of GWP_{100}, 2019 (Gt-CO_2eq)[c]
CO_2	37.9	1	1	38
CH_4	0.379	79.7 (non-fossil) 82.5 (fossil)	27.0 (non-fossil) 29.8 (fossil)	11
N_2O	0.00974	273	273	2.7

CO_2 emissions include emissions from fossil fuel combustion and industry. 2019 emissions use fossil CH_4 GWP.
[a]2019 emissions from Minx et al.[5]
[b]$GWP_{20/100}$ of CH_4 and N_2O as reported by IPCC.[6]
[c]2019 CO_2eq emissions use fossil CH_4 GWP.

As governments and industries pledge to reach net-zero emissions with a focus on peaking CO_2 emissions, the roles of CH_4 and N_2O emission mitigation are often unclear in such commitments.[9] In the cases where governments have made specific commitments to reduce CH_4 and N_2O emissions, the targets have not been stringent enough.[10] Modeling results indicate a need to accelerate mitigation of N_2O and CH_4 until the mid-century and beyond.[11,12] Figure 2 shows the projected CH_4 and N_2O emissions over time in scenarios constraining end-of-century temperature rise to 1.5°C and 2°C globally. Figure 2 shows that the median CH_4 emissions would need to decrease by 24% in the next decade and by 46% by 2050 to keep global temperature increase below 2°C. The required reductions are much more aggressive for 1.5°C-compatible pathways for which 34% reduction is needed within the next decade. The median rate of N_2O emissions reduction required to limit warming to 1.5°C through 2100 is 11% in the next decade and 25% by 2050. These reductions will require technology development across the various sectors in which CH_4 and N_2O emissions occur and policy support in the form of market-based mechanisms.[13,14]

Indeed, policy support for reducing CH_4 and N_2O emissions is growing worldwide. For example, the recent Joint US-EU Global Methane Pledge aims at reduction of CH_4 emissions by 30% over the next decade.[16] However, incentivizing CH_4 and N_2O emissions reductions is complex and arguably more difficult than incentivizing CO_2 emission reductions for multiple reasons. First, the magnitude of these emissions involves considerably higher uncertainty than CO_2 emissions.[17–19] While most CO_2 emissions arise from point sources, CH_4 and N_2O emissions often result from dispersed sources which make estimation complex. Estimation of net CH_4 emissions is further compounded by the complexity of CH_4 sinks, which are largely in the form of hydroxyl radicals. The radicals are unstable; their concentrations must be evaluated using proxy compounds.[20] Atmospheric concentrations of these radicals are estimated with multiple atmospheric chemistry models that use different methodologies and therefore produce different CH_4 sink estimates. Next, the degree to which these must be incentivized depends on assumptions about their atmospheric lifetimes and whether some technological options actually prove effective in reducing life cycle emissions over time.[21] Finally, modeling groups may adopt an underlying assumption that shifts to low-carbon energy (e.g., renewables) will automatically reduce CH_4 emissions, but this is not true. Even if fossil fuels are completely phased out, abandoned coal mines and oil wells will continue to emit CH_4.[22,23] Additionally, most CH_4 emissions originate from sectors where energy transitions will have limited impacts (Figure 1A). Agricultural and waste management activities contribute over 43% and 21% of global CH_4 emissions, respectively (agricultural activities in Figure 1A include "enteric fermentation," "rice cultivation," and "manure management"). Similarly, energy transitions are likely to have limited impacts on N_2O emissions, almost 70% of which are driven by agricultural soil nutrient management ("managed soils and pastures" and "synthetic fertilizer application" in Figure 1B).

Objectives and rationale for this paper

Several publications present high-level global- and national-scale emissions data and discuss mitigation strategies[24,25] or detailed analyses regarding emissions in specific sectors.[14,26] The high-level analyses have focused on the roles of CH_4 and N_2O in climate change and the need for mitigation policies. For instance, the most recent iteration of the IPCC Assessment Cycle, for the first time, calls attention to CH_4 and other short-lived climate forcers.[24] This was also one of the key features of the United Nations Environment Programme Emissions Gap Report.[25] At the national scale, Melvin et al.[14] have summarized the impacts of the U.S. Federal Government's initiatives to reduce CH_4 through regulatory approaches.

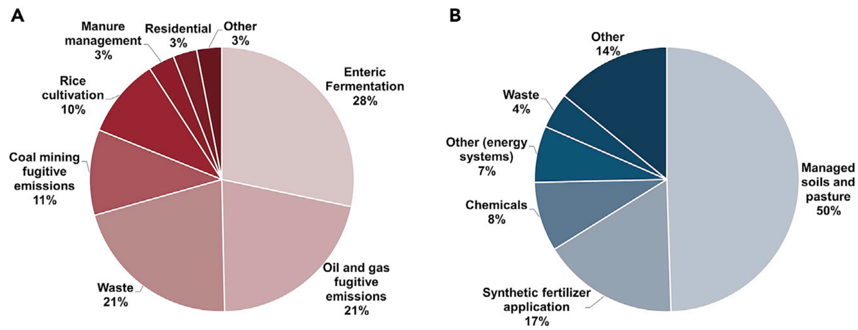

Figure 1. Global antropogenic (A) Methane and (B) nitrous oxide emissions by source, 2019
Source: Figure based on data from Minx et al.[5]

Detailed analyses have provided insights on sectoral mitigation opportunities, for example, in the coal[27] and livestock[26] sectors. Following these important contributions, there is a need to bridge these scales (global, national, and sectoral) and consider cross-sectoral CH_4 and N_2O mitigation strategies, like carbon markets. Addressing part of this need, Nisbet et al.[28] have provided a comprehensive overview of the techniques for quantifying CH_4 emissions across sectors, highlighting mitigation opportunities and their relevance for achieving end of the century temperature goals. Nisbet et al.[29] continued the discussion of methane emissions mitigation and emphasized the need to understand and develop opportunities for N_2O emissions mitigation as well. To our knowledge, there has not yet been a comprehensive review integrating discussion of CH_4 and N_2O emissions sources, mitigation technologies and costs, and the role carbon markets might play in incentivizing mitigation.

In this paper, after reviewing opportunities for emissions reductions in the sectors that most influence CH_4 and N_2O emissions, we consider the current state of carbon markets in terms of their CH_4 and N_2O provisions. We discuss challenges in assessing actual CH_4 and N_2O emissions reductions and carbon pricing that impede effective design and implementation of emission reduction strategies. Challenges we address include additionality, baseline inflation and perverse incentives, variation in carbon pricing over time, and the atmospheric lifetimes of GHGs. This paper provides a unique, holistic, and harmonized approach to addressing these two GHGs that are often overlooked and offers suggestions toward improved understanding of these emissions and their modeling that will strengthen the treatment of these emissions in carbon markets and climate change policy.

SECTORAL EMISSIONS MITIGATION

This section reviews the key sectors with high CH_4 and N_2O emissions—particularly with reference to the classes of emissions and availability of technologies in the present state-of-the-art and status of their deployment. We then synthesize the costs of GHG avoidance in these sectors and identify low-hanging fruits.

Oil and gas extraction

CH_4 emissions occur in almost every segment of the oil and gas sector including production, processing, transportation, storage, and distribution.[30] The amount of emissions reported from this sector can vary widely because of different measurement or estimation techniques and geographical variations.[31] However, important identified sources include storage tanks, equipment leaks, pneumatic controllers, liquids unloading, associated gas flaring and venting, completions and workovers, and methane slip.[32] Additionally, large amounts of CH_4 emissions are attributed to low production well sites, requiring particular attention for further mitigation efforts.[33,34] In 2019, global CH_4 emissions from oil and gas were 2289 Mt-CO_2e, accounting for 21% of the overall CH_4 emissions.[5] In the same year, CH_4 emissions from U.S. oil and gas reached 197 Mt-CO_2e. Considering U.S.-wide estimates, 68% of emissions occur during the production stage, and about 25% of the emissions in the sector are associated with gas processing, transmission, and storage. The contribution from the distribution stage is 7% of overall oil and gas CH_4 emissions.[35] Methane emissions are inconsistently measured and reported, complicating comparisons of emissions inventories and life cycle assessments of natural gas systems across sources.[36] For instance, analysts may

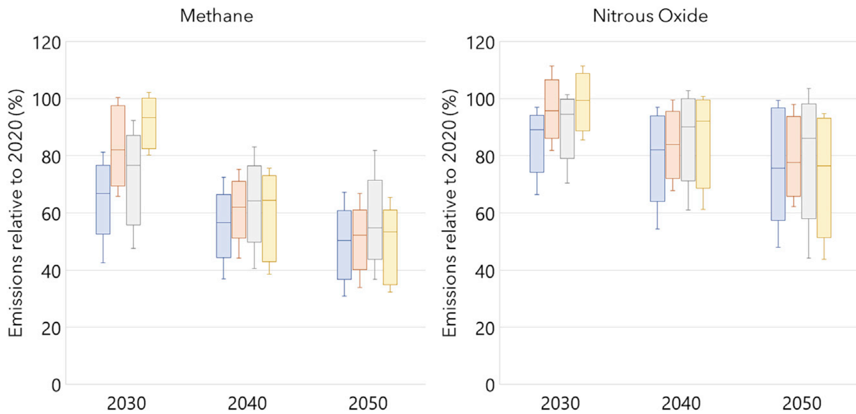

Figure 2. Projected global emissions of methane and nitrous oxide in scenarios limiting end-of-century to 1.5°C and 2°C

Source: Authors' visualizations based on data from IPCC AR6 database.[15] The "likely below 2°C" scenarios represent a 66% likelihood of reaching 2°C by 2100, while the 1.5°C scenarios represent a 50% likelihood of reaching 1.5°C by 2100. "Overshoot" describes a situation where global average temperatures temporarily exceed the warming limit (1.5°C) before 2100.

choose different techniques to allocate methane emissions among co-products (e.g., natural gas, natural gas liquids, and oil).[36]

About 30% of CH_4 emissions may be avoided by refurbishment or replacement of existing infrastructure, installation of new equipment, and by implementing less carbon-intensive processing technologies.[37] Leak detection and repair (LDAR) is one of the most cost-effective CH_4 mitigation alternatives[37] to detect and reduce fugitive CH_4 leaks across the supply chain. LDAR can be deployed across various spatial scales (facility level to continental level), and it is more effective as multiple forms of detection are grouped together.[38] The deployment of well-designed emission detection and repair systems, capable of recognizing abnormally operating facilities or equipment, will play a vital role in reducing CH_4 emissions. Some available technologies are bottom-up such as on-site leak surveys using optical gas imaging, deployment of passive sensors, or mounted on ground-based work trucks at each facility. Bottom-up measurements may be validated through top-down detection using aircraft, satellites, or tower networks, or installation of devices such as vapor recovery units, plungers, and flares.[39] Even though flaring is still considered a source of CH_4 emissions because of incomplete combustion efficiency, it is preferable to releasing CH_4 directly to the atmosphere.[40]

Many of the CH_4 mitigation technologies and practices in the oil and gas sector are mature and have been used for decades though not necessarily in every country.[41] A few technologies such as electric valve controllers for automating oil and gas flow are more recent. Promising initiatives aim to monitor CH_4 emissions on-site using different types of sensors. For instance, continuous, ground-based CH_4 monitoring can provide immediate leakage alerts to operators.[42,43] Such approaches may allow energy companies to find, detect, and repair CH_4 leaks faster. Additional alternatives currently under development consider monitoring networks capable of capturing the characteristic temporal and spatial variabilities of oil and gas CH_4 emissions for detailed emission inventories.[31] In addition, abatement technologies limit loss of valuable, salable natural gas, rendering it a cost-effective mitigation technology.[44]

In fact, more than 50% of leaked CH_4 emissions can be reduced at net-negative costs because income from the sale of recovered CH_4 can offset significant portions of mitigation costs. Nevertheless, there are strong regional differences in these costs. For instance, only 25% of U.S. oil and gas CH_4 can be abated at net-negative costs due to a higher reliance on unconventional production which emits more CH_4 per tonne of gas extracted.[45] When these technologies are not cost effective, replacing high-emitting devices with lower emitting options may require policy and regulatory intervention. For example, the World Bank and its partners are working toward eliminating flaring through an initiative called "Zero Routine Flaring by 2030".[46] Current approaches to limiting flaring through regulatory restrictions and financial incentives may, however, encourage deliberate venting.[47] These regulatory restrictions seem effective in the U.S. but their viability may vary

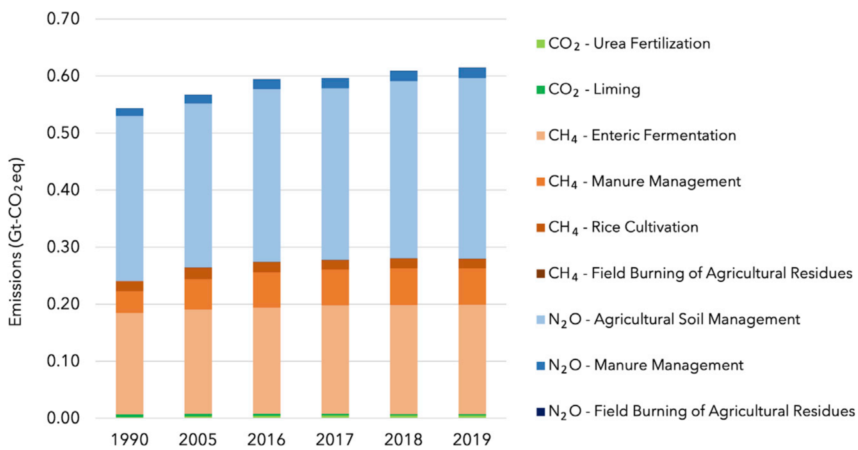

Figure 3. US agricultural GHG emissions

CO_2 emissions from agriculture are in shades of green, CH_4 emissions in orange, and N_2O emissions in blue. Data source: EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks (1990-2019).

elsewhere. Furthermore, the standardization of emissions accounting will encourage reductions as customers demand less GHG-intensive CH_4. For instance, the MiQ standard intends to certify facilities that meet certain performance in an independent and third-party-audited system.[48]

Agriculture

Agricultural activities are major contributors to both N_2O and CH_4 emissions. Agricultural activities account for about 12% of all GHG emissions in terms of GWP_{100} (Table 1 and Figure 1), and almost all of these emissions are in the form of N_2O and CH_4 (Figure 3). Agricultural soil, pasture management, and synthetic fertilizer application are the largest global contributors of N_2O emissions in each region of the world. Together they contribute almost 70% of all anthropogenic N_2O emissions globally (Figure 1). In addition, 87% of the global N_2O emissions increase from 2007 to 2016 is primarily due to feedbacks between climate change and nitrogen additions to soil.[18] CH_4 emissions from enteric fermentation and manure management constitute about 30% of global anthropogenic CH_4 emissions (Figure 1).

There are both direct and indirect sources of N_2O emissions in agricultural systems. Direct agricultural N_2O emissions occur through the microbial processes of nitrification and denitrification of mineral nitrogen in soil, fertilizer, or manure. Direct emissions can also be a result of nitrification and denitrification occurring in manure management systems.[49] Indirect N_2O emissions occur after nitrogen is transported away from a site through surface runoff or leaching of nitrogen into groundwater and surface water.[49] Fertilizer nitrogen losses to the environment via runoff and infiltration from agricultural fields are responsible for 15%–20% of global N_2O.[18]

Agricultural CH_4 emissions are primarily driven by enteric fermentation and manure management, but cultivation of water-intensive crops like rice also contributes notable levels of emissions. Enteric fermentation, a digestion process of ruminant livestock like beef and dairy cattle, produces CH_4. Enteric fermentation emissions make up over 25% of all US agricultural GHG emissions (Figure 3). CH_4 emissions from manure and water-intensive crops are a result of anaerobic decomposition of organic matter in soil, manure storage sites, and in water-saturated fields.

Technologies and strategies for reducing N_2O emissions revolve around maximizing nitrogen use efficiency in agricultural systems. Abatement strategies in agriculture are categorized by the 4Rs: right rate (most economically favorable amount of nitrogen applied), right time (during peak crop N demand), right source (reducing use of anhydrous ammonia), and right place (incorporating N bands into soil).[50] Precision farming, which uses sensors, information technology, satellite systems, and variable rate technology (VRT), is one pathway to be able to accomplish the 4Rs in practice.[51] Nitrification inhibitors, which reduce the production of nitrate from the soil, can also be used to reduce N_2O production in soils.[52] Soil pH management through liming has also been shown to reduce N_2O emissions.[53] The costs of these strategies and technologies impact adoption rates. Nitrification inhibitors can increase the cost of fertilizer, which can cut into the profits of the farm.[54] Simply applying less nitrogen fertilizer can reduce both costs and emissions but could also result in lower yields, resulting in reduced profits.[54] Some strategies, like VRT, are more economically feasible for larger farms. VRT has the potential to increase yields, decrease fertilizer application, and improve crop quality, especially in fields with high spatial heterogeneity.[55] However, smaller farms are less likely to see economic benefits from VRT implementation because of infrastructure costs. On farms less than 200 acres, VRT implementation has an estimated capital cost per acre of $88, while the capital cost of VRT for farms that are 1000 acres is $22 dollars per acre.[54]

Strategies to mitigate CH_4 emissions from agriculture include reducing CH_4 emissions from enteric fermentation, improving manure handling, and enhancing management practices in farming of water-intensive crops. CH_4 emissions from enteric fermentation may be reduced by providing more fats and oils to the diets of ruminant livestock and using antimicrobial agents like ionophores.[56] Emissions from manure storage can be mitigated by increasing aeration through bedding material selection. Composting also increases aeration of manure piles, thereby reducing CH_4 emissions.[57] CH_4 emissions from manure can also be captured and used for energy.[58] Soil CH_4 emissions are dependent on many factors such as soil type, weather, tillage, fertilizer usage, and crop residues. CH_4 emissions are greater in farms where soil flooding is practiced, such as paddy cultivation in countries like India and China.[59,60] These two countries are the top two producers of rice in the world, accounting for about half of the world's rice production.[61,62] This technique is relatively less common in the United States which produces only 2% of the world's rice.[61] In many cases, other technologies such as mid-season drainage and intermittent irrigation have also been shown to reduce CH_4 emissions from water-flooded fields.[63,64]

Various polices have been developed to encourage famers to adopt practices to manage N_2O emissions in their agricultural systems. In the United States, the Climate Action Reserve's voluntary Nitrogen Management Protocol guides farmers to reduce N_2O emissions for selected crops in selected states by improving their nitrogen use efficiency. These practices include a required reduction in the use of synthetic nitrogen and optional use of enhanced efficiency fertilizer.[65] Some of these practices can reduce N_2O emissions by as much as 50%, but many variables such as climate, soil type, and crop selection can all play a role on the site-specific impact these techniques can have.[50] In the northern central U.S., the Delta Nitrogen Credit Program encourages corn farmers to implement the 4R N_2O abatement strategies by offering financial credits.[66] Despite these and other programs, N_2O emissions from agricultural soils have increased by about 10% since 2012.[67] This is driven both by continued increases in average nitrogen fertilizer application to crops like corn, and increases in total production. For example, U.S. corn production has increased by 25% from 2012 to 2021, primarily for livestock feed and ethanol production.[61,68] In the European Union (EU), the Nitrate Directive (91/676/EEC) pushes for reduced nitrogen fertilizer use and optimization. Between 2000 and 2008, this policy led to about a 6% reduction in N_2O emissions for member EU nations.[69]

Several bills have been passed and programs undertaken in the U.S. and around the world to aid the cause of mitigation of CH_4 emissions from agriculture. The Zero Carbon Amendment Bill in New Zealand targets the reduction of CH_4 emissions from agriculture by 10% by 2030 and by 24%–47% by 2050.[70] The ARB Compliance Offset Program in California, together with Senate Bill 1383 on Climate short-lived pollutants has set a target of reducing biogenic CH_4 emissions by 40% by 2030 from 2013 levels.[71,72] At the national level in the U.S., there are efforts to develop animal feeds that will reduce CH_4 emissions from enteric fermentation.[73] For handling CH_4 emissions from manure decomposition, the prevalent strategy has been to produce biogas from anaerobic digestion (AD) of manure.[74] Biogas may be used directly as a combustion fuel or upgraded to renewable natural gas by removing all constituent gases except CH_4, which is 50%–60% of biogas by volume. As of January 2019, there are about 248 anaerobic digestors on livestock farms and 34 more under construction.[75] As for soil CH_4 emissions, as mentioned before, CH_4 mitigation techniques like intermittent irrigation and mid-season drainage are practiced in India and China, respectively.[63,64] Although these techniques can increase N_2O emissions from soils, prevention of excess fertilizer usage can still result in net benefits.

Waste

Landfilling activities

In landfills, anaerobic decomposition of organic material in municipal solid waste creates CH_4, which along with CO_2 and other gases constitute landfill gas (LFG). CH_4 is roughly 50% of the emitted LFG.[76] CH_4

emissions from landfills were approximately 15% of U.S. CH_4 emissions in 2019 and ranked third in anthropogenic CH_4 emission sources.[76] The quantity and composition of LFG are mainly influenced by the local climate and the age, type, quantity, and composition of the waste the landfill contains.[77]

LFG can be captured and converted into energy. To accomplish this, piping buried in the landfill collects gas. Processing then removes moisture and impurities (e.g., siloxane/sulfur) from the gas. The collected and processed LFG is commonly used in one of three ways[76,77]:

- Direct electricity production (68%): This can be done with an internal combustion engine, gas turbine, microturbine, combined heat and power technology, and combined cycle technology (combined gas turbine and steam turbine).
- Direct heat production (17%): LFG has a lower heating value of roughly 18 to 20 MJ/m^3 (50%–55% of CH_4 (v/v)). When used as a fuel, LFG is generally combusted in a boiler or used in a direct thermal application (kilns, process heater, etc.). Landfill leachate evaporation is another application.
- Renewable natural gas (15%): LFG can be further cleaned and purified to remove CO_2 and impurities (e.g., N_2 and O_2), producing the equivalent of natural gas that can be compressed or liquefied. The cleaned gas can be directly injected into a natural gas pipeline.

Globally, there are more than 1,000 LFG plants. Most of them are located in the EU and the U.S.[78] In the EU in 2020, 1645 metric kilotons of oil-equivalent primary energy (69 PJ) were produced from landfill gas.[79] In terms of volume, the U.S. captures the most LFG in the world.[80] As of 2021, 550 LFG energy projects were in operation in the U.S.[77,81] Approximately 70% of these projects generate electricity, using mostly (85%) internal combustion engines.[77] About 17% of LFG projects use the gas directly as fuel. The remaining projects (13%) produce renewable natural gas.[77] For many developing countries, a comprehensive action plan that incentivizes collection and utilization of LFG does not yet exist. Inability to collect sufficient amount of LFG from landfill sites and lack of research on the LFG generation mechanism and forecast are major technical challenges for developing countries.[82]

Wastewater treatment

Combined, domestic, and industrial wastewater treatment were 2.8% of 2019 CH_4 emissions in the U.S. (18.4 MMT CO_2e), with domestic wastewater comprising two-thirds of these emissions.[83] Wastewater treatment is also a significant contributor to N_2O emissions, with the sector contributing about 5.8% (26.4 MMT CO_2e) of U.S. N_2O emissions.[83]

CH_4 emissions occur wherever anaerobic conditions are present in the wastewater treatment process. For on-site treatment methods, such conditions are prevalent in lagoons and septic tanks, where sludge settles and is digested under anaerobic conditions.[84] The resulting CH_4 escapes if the lagoon is uncovered and is vented from septic tanks, making these treatment methods relatively large sources of CH_4 within the wastewater treatment field. In the U.S., for instance, it is estimated that 48.1% of CH_4 emissions from domestic wastewater treatment in 2019 arose from septic tanks.[83] For centralized wastewater treatment systems, anaerobic conditions exist in sewers, anaerobic sludge reactors and digesters, storage tanks, and areas where sludge degrades.[85] Lagoons can also be used in centralized wastewater treatment. Additionally, dissolved CH_4 remaining in wastewater effluent can be released once it enters larger water bodies.[83] 7.5% of CH_4 emissions from domestic wastewater treatment in the U.S. were from centrally treated aerobic systems, 27.7% were from centrally treated anaerobic systems, 1.7% were from anaerobic sludge digesters, and 15% were from centrally treated wastewater effluent in 2019.[83] As tabulated by Daelman et al., CH_4 emissions from centralized wastewater treatment systems can range from 0.08%-1.2% of influent chemical oxygen demand . Approximately 72% of these emissions arise from the unit processes involved in anaerobic sludge digestion, namely the "the gravitational thickener for the primary sludge, the centrifuge, the buffer tank for the effluent of the digester, the storage tank that contains the dewatered sludge, and the methane slip from the gas engines."[85] In general, anaerobic digesters are often used to generate CH_4 that is subsequently utilized as an energy source at the wastewater treatment plant; however, CH_4 emissions can occur from leaks along the process train, uncovered tanks, and incomplete combustion of the produced biogas.[83,86] Leaks from biogas and biomethane supply chains in particular may be responsible for up to 0.0185 Gt CH_4 emissions per year,[87] almost 5% of the 2019 global CH_4 emissions reported in Table 1. CH_4 can be emitted from centralized aerobic wastewater treatment processes as well. The sewers used to collect wastewater foster anaerobic environments, and aerobic processes can subsequently release this trapped CH_4.[83]

N_2O emissions occur because of nitrification and denitrification of nitrogen-containing compounds such as ammonia in wastewater. Nitrogen, typically in the form of ammonia in wastewater, is turned into nitrite by ammonia-oxidizing bacteria, and then the nitrite is converted into nitrate by nitrite-oxidizing bacteria. However, N_2O can be produced as a byproduct of nitrifying bacteria, particularly ammonia-oxidizing bacteria in anoxic conditions. Additionally, because various groups of bacteria are responsible for the denitrification of nitrogen-containing compounds, incomplete denitrification can occur, causing N_2O to be produced instead of diatomic nitrogen. About 90% of N_2O emissions can be attributed to the activated sludge units in the plant, while the rest of the emissions are from sludge and grit storage tanks. The produced N_2O in the activated sludge units largely comes from anoxic denitrification, with aerobic denitrification and nitrifier denitrification also playing a role.[88] Finally, N_2O can also be formed because of the chemical reactions that organic and inorganic compounds undergo in the presence of nitrate and hydroxylamine.[88]

For areas using lagoons for wastewater treatment, covering these lagoons to trap and recover CH_4 is the most readily implementable emissions reduction technology.[84] Similarly, capturing and combusting the CH_4 vented from septic tanks reduces the CH_4 emissions from on-site systems. If possible, constructing centralized wastewater treatment plants that utilize aerobic reactors in coordination with anaerobic digestion (AD) is optimal, provided that the CH_4 produced from AD is captured and utilized as a fuel source and minimal leakage occurs along the sludge treatment train.[84]

N_2O emissions from a wastewater treatment plant can either be minimized through adjusting operating conditions or introducing new technologies to capture N_2O after it is formed. Optimizing operating conditions at these plants could reduce N_2O emissions without introducing any new technologies. For instance, operating at higher solid retention times helps to maintain low concentrations of nitrogen and ammonia in the wastewater, reducing the amount of N_2O emissions.[89] Denitrifying bio-scrubbing is a technology currently under development for side stream wastewater treatment to remove the N_2O as it is formed.[90] However, these technologies require long hydraulic retention times in large biofilters and, therefore, high capital cost.[90] In addition to capturing N_2O, there are processes in development, such as the Coupled Aerobic-anoxic Nitrous Decomposition Operation (CANDO) process, that intentionally produce N_2O for various uses.[91] For example, N_2O gas can be used as an oxidizer in the combustion of CH_4 from AD for increased energy production efficiency[91] or in converting propylene to propylene oxide or methane to methanol.[92]

Globally, regional differences in wastewater treatment infrastructure highlight the need for a variety of technology options to reduce CH_4 emissions. There is a close correlation between a country's income level and the level of wastewater treatment. Low-income countries treat ~8% of generated wastewater whereas high-income countries treat ~70% of generated wastewater.[93] In the developing world, where septic tanks and anaerobic lagoons tend to be the dominant methods of wastewater treatment, covering lagoons and properly maintaining septic tanks are the most readily available options for reducing wastewater-associated CH_4 emissions.[94] Future work toward developing centralized wastewater treatment systems will be costly but can be accomplished via various international funding efforts.[95] In developed countries with centralized wastewater treatment systems in place, there are numerous opportunities to reduce CH_4 emissions. As of 2017, in the U.S., ~81% of wastewater is treated via the country's 14,748 wastewater treatment plants; however, only 1,269 of these plants feature anaerobic digestion (AD), which are used to intentionally produce and capture CH_4.[96] Upgrading existing plants and including AD as part of new plants is critical for reducing CH_4 emissions and increasing the energy efficiency of wastewater treatment, but this can have high capital cost. Performance contracting, public-private partnerships, federal funding allocated via the Clean Water State Revolving Fund, and local municipal funding will likely play integral roles in these upgrades.[95–97] Furthermore, new innovations continue to drive toward energy efficiency, neutrality, and even energy positivity at wastewater treatment plants. Approximately 216 wastewater treatment plants in 2014 were known to co-digest food in their anaerobic digesters, with some plants able to satisfy their full energy needs and even supply excess energy back to the grid via this co-digestion.[98] New reactor designs, such as submerged or side-stream anaerobic membrane bioreactors (AnMBRs), can also significantly reduce the reactor sizes and energy requirements for AD.[99]Additionally, other nascent technologies such as the CANDO process could be combined with AD to enhance the heat value obtained from CH_4 combustion, and still other technologies in development could harness CH_4 to produce bioplastics or remove both CH_4 and nitrogen at once.[99] For now, these developments are at various stages in the scale-up process.

N_2O mitigation strategies for each wastewater treatment plant will also depend on existing configurations, operating conditions, and technologies. As a result, there is no single strategy that can be taken to reduce N_2O emissions, and priority should be shifted to the conditions that most influence N_2O emissions. For example, in the developing world where decentralized treatment largely occurs, N_2O emissions play a minor role in the global N_2O footprint. N_2O emissions from septic tanks, for example, make up less than 2% of total fugitive greenhouse gas emissions.[100] The much lower emissions, combined with the high capital cost of N_2O emission reduction technologies, make it difficult to justify investing in additional N_2O mitigation for these treatment facilities. For centralized wastewater treatment plants, implementation of N_2O mitigation technologies has been limited despite an increase in studies demonstrating their feasibility. This is due to a combination of lack of incentive, high capital cost, and technical challenges associated with integrating these technologies into existing infrastructure.[101]

Coal mining

Coal production (mining) drives >95% of coal sector CH_4 emissions. The remaining CH_4 emissions occur during post-mining handling. CH_4 emissions during coal exploration are minimal.[102] Coal is mined from deep-seated deposits (i.e., underground mining) and from shallower deposits (i.e. surface mining). Surface mining emissions are considerably lower (0.3–2 m^3-CH_4/t-coal) than those from underground mining (10–25 m^3-CH_4/t-coal).[103] There are strong regional emissions patterns present among the major coal producers. For instance, China mines >90% of the coal it produces from underground mines. China provides over half of the world's coal. Therefore, its practices significantly affect global CH_4 emissions from coal mining.[104] On the other hand, >90% of India's coal mining is surface based.[105] Though this represents 10% of the global coal production that is less CH_4-intensive than underground mining, surface mines may be less motivated to reduce emissions because of comparably limited mitigation and revenue generation opportunities. The extent of CH_4 emissions from abandoned coal mines depends on their operational conditions. Flooded abandoned mines do not produce appreciable CH_4.[106]

Commercial coal mine methane (CMM) recovery technologies have been in use since the 1980s. CH_4 can be recovered from virgin coal beds (i.e., where mining has neither taken place nor is it likely to), using technologies similar to shale gas extraction. Pre-mining CH_4 drainage or CMM recovery has also been commercialized where simultaneous recovery of coal and CH_4 takes place. This has the important co-benefit of improving safety for underground mine workers.[107] More recently, ventilation air methane (VAM) recovery has been increasingly adopted. VAM captures dilute concentrations of CH_4 from the ventilation air, concentrates it, and co-combusts it with other byproducts from coal washing and conversion.[108]

A combination of CMM and VAM recovery reduced CH_4 emissions by 50%–70% in some coalfields.[109] The extent of use of these mitigation technologies varies globally. For example, until the shale gas boom, the U.S. virgin coalbed methane supplied 10%+ of total natural gas production. CMM and VAM have been utilized in China and Australia, respectively. Several other countries have favorably assessed the commercial and emissions reduction potential of CMM. Recovery of CH_4 from abandoned mines has been carried out in some regions though there is a lack of exploration globally of the abandoned mines and their gas extraction feasibility.[102]

Chemical industry

Most N_2O emissions from the chemical industry can be attributed to just two manufacturing processes: the production of nitric acid and adipic acid. In nitric acid production, N_2O is formed as a byproduct of high temperature catalytic oxidation of ammonia and released from vents into the atmosphere. In the production of adipic acid, N_2O is formed when nitric acid is used to oxidize either cyclohexanone or cyclohexanol. The N_2O that is formed is emitted into the atmosphere in the gas waste stream. In the USA, N_2O emissions from adipic acid and nitric account for about 3% of total N_2O emissions.[67]

Many abatement technologies exist to reduce N_2O emissions for nitric acid production. N_2O abatement technologies can be broken down into four groups: primary, secondary, tertiary, and quaternary measures.[110] The technologies are placed into one of the four groups based on the process location of the device. Primary measures are those that prevent N_2O from forming in the ammonia burner. Secondary measures remove N_2O from the burner after the ammonia oxidation catalyst, which is located between the ammonia converter and adsorption column. Tertiary measures remove N_2O from the tail gas after it exits the adsorption column. Finally, quaternary measures remove N_2O from the tail gas after it goes through an expander. Commonly used N_2O abatement technologies for nitric acid production are considered secondary or tertiary. These technologies include catalytic destruction and thermal decomposition, which break the bonds in N_2O and produce nitrogen and oxygen. Non-selective and selective catalytic reduction are additional tertiary measures that reduce N_2O emissions, although the technology is typically installed for NO_x reduction. Primary and quaternary technologies are currently in development but have not been used on an industrial scale.

Similar technologies are used to reduce N_2O emissions in adipic acid production. Catalytic destruction and thermal destruction decomposition are the most common technologies installed.[111] However, additional opportunities to reduce N_2O emissions exist within the adipic acid industry through recycling the N_2O to produce nitric acid or using N_2O as an oxidant to produce phenol.[112]

Many existing adipic acid plants have had N_2O abatement technologies already installed in the process. Of the 23 adipic acid plants that are known to exist globally, nine of them are believed to currently run without N_2O abatement technologies. Five of these plants are in China, two are in Ukraine, and Japan and South Korea each have one.[112] Installation of abatement technologies at each of these sites could help to minimize the amount of N_2O emissions released from adipic acid production. The other 14 plants have installed various N_2O abatement technologies, reducing N_2O emissions by as much as 90%.[112] Some of the remaining emissions are due to planned and unplanned downtimes of the N_2O abatement device. These emissions can be reduced by installing backup N_2O abatement technologies, to ensure that the technology is always available for use during plant operations. Doing so has the potential to increase N_2O emission reductions from 90% to 97%.[112]

The status of implemented N_2O abatement technologies for nitric acid is not fully understood. For the 500 to 600 nitric acid plants that exist globally, there is no comprehensive inventory discussing implemented abatement technologies.[113] This is because nitric acid production is typically integrated into chemical facilities that produce multiple products. However, plants producing nitric acid in the EU have had success in reducing N_2O emissions due to pollution control measures and the EU Emissions Trade Scheme (ETS) obligating GHG emissions for the manufacturing plants throughout the region. Since 1990, N_2O emissions from the EU's approximately 100 nitric acid plants have dropped by 93%.[114] In the United States, nitric acid plants do not typically use N_2O-specific abatement technologies, but non-selective catalytic reduction technologies are believed to be installed in some of the older plants. Although these technologies reduce N_2O emissions between 80% and 90%, they are not an acceptable abatement technology in new plants because they are energy intensive. Newer targeted N_2O abatement technologies are not believed to be used. As a result, the United States N_2O emissions reductions from nitric acid production have been much smaller, with only about an 8% reduction since 1990.[67] Installation of abatement technologies in nitric acid production in the US and other parts of the world remains a major opportunity to reduce N_2O emissions.

Fuel combustion activities

N_2O emissions occur as a byproduct of combustion. They occur from both stationary combustion (e.g., coal-fired power plants) and mobile combustion (e.g., internal combustion engines in vehicles) and are maximized at combustion temperatures between 800 K and 1200 K. Other conditions that impact N_2O emission from combustion are the operating pressure of the combustion gasses and oxygen concentration.[115] N_2O emissions from stationary combustion make up about 6% of US N_2O emissions, while mobile combustion is about 4%.[67] CH_4 emissions also occur as a byproduct of combustion. However, stationary and mobile combustion combined only contribute to about 1.9% of total methane emissions in the US.[67]

For both stationary and mobile combustion, N_2O-specific abatement technologies are limited. This is because the N_2O concentrations in flue gas streams are very low. For mobile combustion, most N_2O emissions occur from road transportation. The main technology to reduce N_2O emissions from road transportation is the catalytic converter. Although catalytic converters initially increased N_2O emissions from vehicles, continued improvements to meet stricter pollutant standards have enabled N_2O emissions from

Table 2. Sectoral costs and potential of mitigation for CH_4

	Emissions, Mt-CO_2e, 2019	Mitigation potential in 2050 (Mt-CO_2e)				Total mitigation potential in 2050, Mt-CO_2e
		< \$0/t-CO_2e	\$0-50/t-CO_2e	\$50-100/t-CO_2e	>\$100/t-CO_2e	
Oil and Gas	2,161	1,540	868	28	196	2,632
Coal Mining	1,058	168	532	0	28	728
Landfilling	2,274	1,568	196	28	84	1,876
Wastewater	512	280	308	28	28	644
Agriculture and livestock	4,531	280	672	28	28	1,008
Total	10,536	3,836	2,576	112	364	6,888

Data sources are Minx et al. (2021) for emissions[119], Winiwarter et al.[118] and Höglund-Isaksson et al.[120] for costs.

mobile combustion to decrease by 61% since 1990.[67] For stationary combustion (specifically for coal), modifications to fluidized bed technologies have shown potential to reduce N_2O emissions through reverse air staging or using an afterburner. An afterburner adds a secondary fuel to the combustion chamber to raise the total temperature of the gases and can reduce N_2O emissions by 90%.[116] Reverse air staging adds more oxygen to the bottom part of the combustion chamber and less to the upper part of the combustion chamber, and has shown to reduce N_2O emissions by about 75%.[117]

Cost and potential of mitigation by sector

The individual sectoral subsections describe the vast diversity in approaches to mitigate CH_4 and N_2O from a variety of sectors. Tables 2 and 3 summarize CH_4 and N_2O emissions, respectively, and literature-based[5,118] mitigation potential by sector. CH_4 mitigation is often considered to be economically beneficial because the revenue from the recovered CH_4 may offset the costs. In Table 2, it is evident that very significant amounts of CH_4 emissions can be mitigated at net-negative (<\$0 t/CO_2e) costs. The overall share of mitigation potential at <\$0/t-CO_2e is 59%, 23%, 84%, 43%, and 28% in the oil and gas, coal, waste, wastewater, and agriculture sectors, respectively. The oil, gas, and waste sectors can alone provide mitigation of >3 Gt-CO_2e annually with net revenue generation. This is because of the availability of low-cost mitigation options in these sectors, coupled with the substantial price of CH_4 in the current market. The cost of mitigation is provided sectorally because the cost of individual technologies within a sector may be highly variable. For instance, while some LDAR technologies in the oil and gas sector may cost <\$0/t-CO_2e, others may cost much more (Table 2). As such, an exact correspondence of costs to individual technologies is highly region specific.

CH_4 mitigation recovers a salable product which lowers mitigation costs. N_2O mitigation lacks a similar economic driver. Nonetheless, the costs for N_2O mitigation are also low, with ~80% of mitigation potential below \$10/t-CO_2e. As Table 3 shows, the current carbon price in several markets is well above this threshold. Even at the lower end of the pricing spectrum, the Chinese market currently trades at ~\$10/t-CO_2, which could provide an effective price point to mitigate most CH_4 and N_2O emissions. However, the exclusion of CH_4 and N_2O from many market mechanisms disincentivizes the low-cost mitigation of these emissions compared to mitigating CO_2 emissions.

NON-CO_2 PROVISIONS IN GLOBAL CARBON MARKETS

The mitigation prices discussed in the above section do not account for market mechanisms. GHG mitigation costs can be influenced by carbon markets, which are active at multi-national, national, and subnational levels. They are a combination of voluntary and non-voluntary, or compliance, markets. The type of carbon pricing mechanism used in these markets generally falls into two categories: cap-and-trade systems and carbon taxes. With the goal of limiting or reducing GHG emissions, carbon markets cover various GHG-emitting sectors and account for emissions from several GHGs beyond CO_2, although in some cases CH_4, N_2O, or fluorinated gases—such as perfluorocarbons (PFCs), sulfur hexafluoride (SF6), and hydrofluorocarbons (HFCs)—are not included. Irrespective of the jurisdictional level and requirement for compliance, there is significant variance in the way in which these markets deal with non-CO_2 gases. While most carbon markets do include incentives for CO_2 mitigation, only a subset of these incorporates incentives for CH_4 and N_2O. Understanding the level of coverage of non-CO_2 incentives is necessary because the costs

Table 3. Sectoral costs and potential of mitigation for N_2O

	Emissions, Mt-CO_2e, 2019	Mitigation potential in 2050 (Mt-CO_2e) <\$10/t-CO_2e	\$10-100/t-CO_2e	>\$100/t-CO_2e	Mitigation potential in 2050, Mt-CO_2e
Combustion	240	0	5	0	5
Industry	277	104	0	0	104
Agriculture	2,018	77	43	6	126
Wastewater	126	25	0	0	25
Total	2,661	206	48	6	260

Data sources are Minx et al.[5] for emissions; Winiwarter et al.[118] and Höglund-Isaksson et al.[120] for costs.

mentioned in Tables 2 and 3 do not uniformly apply across geographies. In this section, we first discuss the scope of voluntary carbon markets and then non-voluntary markets, with a focus on nations or regions that have enacted cap-and-trade systems and their coverage of non-CO_2 emissions.

A widespread voluntary carbon market, and one of the first enacted, is the Clean Development Mechanism (CDM). Established under the Kyoto Protocol in 2006, the CDM enables countries with emissions-reduction commitments to implement emissions-reduction projects in developing countries.[121] The CDM allows developing countries to earn tradeable, salable certified emission reduction (CER) credits, each equivalent to one metric ton of CO_2. The dual purpose of the CDM is to aid industrialized nations in fulfilling their emissions-reduction targets and to help developing countries achieve sustainable development. Additionally, the CDM is the main source of income for the United Nations Framework Convention on Climate Change Adaptation Fund, which finances adaptation projects and programs in developing countries vulnerable to the adverse effects of climate change through a 2% levy on CERs.[122]

To date, there have been over 7,000 CDM projects. Example projects include solar panels in rural areas and energy efficient boilers.[123] Several CDM projects directly relate to reducing CH_4 emissions, such as recovery and utilization of gas from oil fields that would otherwise be flared or vented, landfill gas capture, and abatement of CH_4 from coal mines.[124] Figure 4 shows the average investment costs and host countries of CDM projects involving CH_4 and N_2O emissions. In total, CDM projects have reduced 71 t-CO_2e of CH_4 across developing countries in Asia and Africa. Most reductions, 38 t-CO_2e, have occurred in China and among project activities, most reductions have been associated with refinery leaks and flare recovery.[123] Beyond its roles in achieving emissions reductions and assisting sustainable development, the CDM has provided a foundation for market mechanisms that can be studied and improved upon in the future.[125]

In addition to the CDM, there are several voluntary markets that are emissions trading programs and cover CH_4 emissions. The Climate Action Reserve (CAR) is a non-profit organization based in California that establishes standards for developing and verifying GHG emissions-reduction projects in the U.S. and Mexico.[127] Another non-profit in the U.S., the American Carbon Registry (ACR) publishes standards, methodologies, and protocols for multiple project types involving CH_4, such as livestock, landfills, and coal mines. The Verified Carbon Standard (VCS) program, which uses methodologies from the CDM but allows project developers to design new ones or revise existing ones, has registered 46 coalbed methane projects.[127]

Non-voluntary carbon markets typically exist in the form of cap-and-trade systems, but some regions have also adopted carbon taxes. Cap and trade, also known as emissions trading or emissions trading scheme (ETS), is an approach where a central authority creates allowances equal to the set cap of permissible emissions, and a periodic auction, in which those allowances are traded, leads to a steady carbon price that provides incentive to reduce GHG emissions (CARB, 2020). Cap-and-trade programs distinctly set future emissions targets but allow for carbon prices to vary, whereas carbon taxes set a price that emitters must pay but allow for uncertainty in the level of emissions reductions achieved.[128] Global maps of the price of carbon and GHG coverage in carbon markets are shown in Figure 5.

The EU ETS has historically been the largest carbon market in the world but is now second to Chinas. The EU ETS started in 2005 and now operates in 28 EU member states, Iceland, Liechtenstein, and Norway. The United Kingdom used to participate in this scheme but has replaced it with its own UK Emission Trading

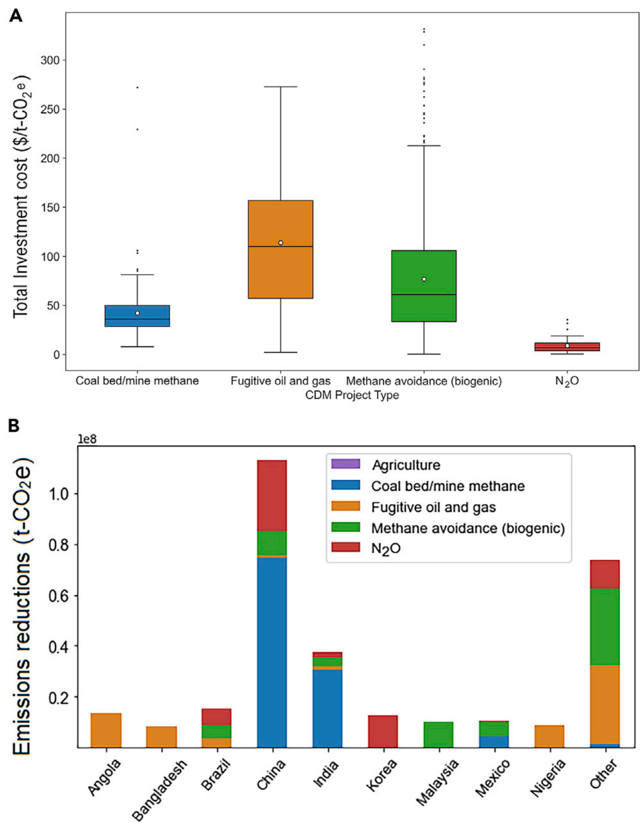

Figure 4. Investments and emissions reductions in various CDM project categories

CDM project non-CO_2 emissions mitigation by (A) project sector types and (B) country.[123] "Coal bed/mine methane" includes the treatment or utilization of CH_4 from coal mines; "Fugitive oil and gas" includes the treatment of fugitive gases from oil and gas production; "Methane avoidance (biogenic)" includes the avoidance, treatment, and utilization of CH_4 from manure, wastewater, palm oil waste, and composting; and "N_2O" includes decomposition from nitric and adipic acid production.[126]

Scheme in 2021. The EU ETS covers around 40% of EU-wide GHG emissions from multiple sectors, including power, manufacturing, and aviation.[129,130] The GHGs covered include CO_2, N_2O, and PFCs. Independently, Switzerland has used a hybrid approach of a CO_2 tax and its own ETS, but as of 2020 its ETS linked with the EU ETS, and GHG-intensive plants in Switzerland participating in the ETS are exempt from the carbon tax.[131]

The China National ETS, now the largest in the world, covering 40% of its GHG emissions, began in 2021. Originally, seven regional pilot ETS programs operated in three-year demonstration periods from 2013–2016.[132] The current national ETS includes only its power sector, coal- and gas-fired power plants, and only CO_2 emissions but aims to expand to seven other sectors in the future.[133] CMM would be a promising addition to the ETS because coal mining is responsible for the largest fraction of China's anthropogenic emissions and current CMM regulations have made a negligible impact on rising CH_4 emissions.[134]

The U.S. does not have a national carbon market but does have several subnational compliance trading schemes. The California Cap and Trade scheme, operated by the California Air and Resources Board (CARB), includes fossil and biogenic CH_4 and N_2O emissions. Current allowance prices are around $17/t-$CO_2$e, which are considerably lower than credits under the low carbon fuel standard with a tax credit for carbon capture worth $135–150/t-$CO_2$e.[135,136] The Regional GHG Initiative (RGGI) in the Eastern states is another operational compliance trading scheme; it includes CH_4 from agriculture and landfills but not from fossil fuel extraction.[137] Several voluntary emissions trading programs in the U.S.—the Climate Action Reserve (CAR), American Carbon Registry (ACR), and Verra's Verified Carbon Standard (VCS)—cover GHGs from fossil fuel extraction, such as coal mine methane.[127] The CAR, ACR, and VCS also have offset protocols

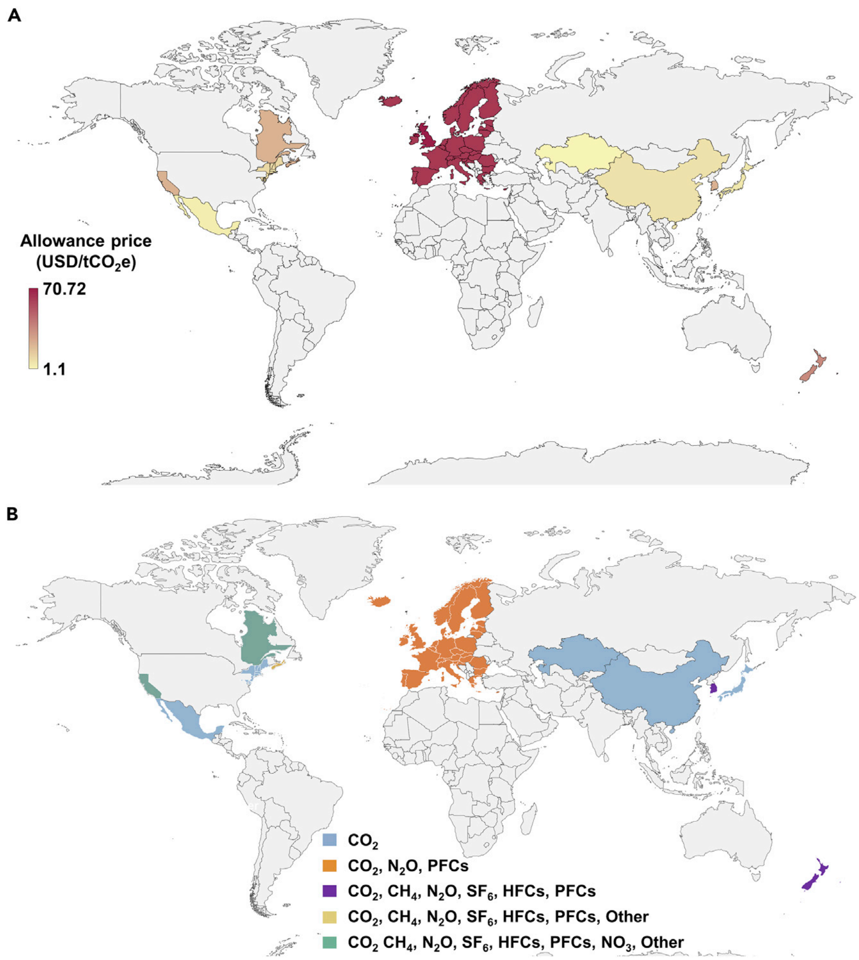

Figure 5. Regional trends in carbon markets

Maps of key carbon markets based on the current levels of (A) carbon price and (B) degree of coverage of GHGs.

for reducing N_2O emissions in agriculture.[138] Beyond these markets, the U.S. only has other non-market initiatives for reducing emissions, such as the EPA's Methane Challenge Program in the oil and gas sector.[139] Some argue for a nationwide carbon tax to avoid emission "leakages" across borders.[140] Such an approach would require substantial policy and regulatory changes.[141]

Several other nations have national or subnational trading schemes with varying degrees of sector and GHG coverage. In Québec, Canada, an ETS was started in 2011 and formally linked with California's in 2014.[142] The Québec program covers 78% of GHG emissions and includes CO_2, CH_4, N_2O, NO_3, and fluorinated GHGs.[143] New Zealand introduced an ETS in 2008 and established a cap on emissions in 2020, covering about 50% of emissions, including CH_4 and N_2O.[144] South Korea's ETS began in 2015, covers 70% of the country's GHG emissions, and includes CH_4 and N_2O.[145]

In addition to trading schemes, there are other financial incentives to reduce GHG emissions currently in action. Subnationally, some states or regions within Brazil, Nigeria, Norway, Russia, and Canada have enacted taxes, fees, or charges for CH_4 emissions. British Columbia, Canada has set a price on carbon since 2008, which has risen to \$45/t-CO_2e in 2021.[146] In the US, a tax credit called 45Q, enacted in 2018, allows industrial manufacturers that capture CO_2 to earn \$50/t-CO_2e if stored permanently and \$35/t-CO_2e if utilized, such as for enhanced oil recovery.[147] However, the 45Q tax credit does not consider CH_4 emissions, either in venting or leakage of natural gas. More recently, the US Congress has passed the Inflation Reduction Act. This enforces a methane charge of \$900/t-CH_4 (increasing to \$1500/t-CH_4 after two years) for specific petroleum and natural gas facilities.[31] This provision accounts for CH_4 emissions directly without converting them to a CO_2-equivalent basis. Such an approach will directly constrain emissions below the preselected threshold. In this sense, conversion to CO_2 equivalents, dependent on time horizons, is avoided, and it opens the need to further CH_4 monitoring improvement.

Economic regulatory tools offer increased flexibility for industry, and recently in the U.S., the American Petroleum Institute, a trade association consisting of oil and gas industry leaders, endorsed carbon pricing policies in its climate action framework.[148] While there is a wide array of regulatory tools, combinations of them could have adverse or positive effects on overall emissions reductions, and their interactions should be studied.[149]

Having considered the coverage of non-CO_2 GHGs in various voluntary and market schemes, we may also consider whether the allowance price in various schemes has been fixed suitably. The social cost of carbon is calculated at $471 to $1500/t-$CH_4$.[150] Considering a GWP_{100} of 28, this translates to $17–54/t-$CO_2$e. As shown in Figure 5A, market costs reach $70/t-$CO_2$e, which falls below the social cost of carbon range but above values proposed for oil and gas operator fees for CH_4 emissions.

Overall, three conclusions can be drawn from this overview of carbon markets. First, the largest markets do not address CH_4 (Figure 5), which is a shortcoming. Second, there are large differences in the mechanisms each program employs which can complicate participation for multi-national or national companies (e.g., in the U.S. where no national policy is in place). These discrepancies impede effective use of markets globally to address the global issue of climate change. Clearly, there is a need for consistent implementation of policies encouraging emissions reductions of non-CO_2 gases, particularly in countries with high fossil fuel and agricultural emissions. Finally, markets can help push adoption of mitigation technologies. Even technologies that are cost effective (Tables 2 and 3) remain underutilized. For example, mitigating >50% of CH_4 emissions would cost less than $0/t-$CO_2$e and 80% of N_2O emissions can be mitigated for under $10/t-$CO_2$e. Consistent and effective use of markets could nudge these cost-effective solutions into broad use.

CHALLENGES WITH IMPACT ASSESSMENT AND PRICING

In this section, we describe five challenges in assessing the GHG emissions reductions associated with CH_4 and N_2O management activities and their values in carbon markets.

Ensuring additionality

Emissions management activities incentivized in carbon markets should be those that satisfy an additionality requirement. "Additional" activities are those that would not have occurred without the carbon market incentive. Activities that would be carried out to comply with government regulations or to increase profits are not considered additional. As a result, many CH_4 and N_2O management activities do not satisfy the additionality requirement because they are either required by regulation or are profitable without carbon markets. In the oil and gas sector, many CH_4 emissions reduction projects are cost effective without carbon revenue, so carbon credits may not be necessary.[151] Similarly, virgin coalbed CH_4 extraction is a separate profitable activity—natural gas extraction—and does not generally fall within the ambit of CDM or other carbon financing.[152] In centralized wastewater treatment systems, CH_4 emissions reductions achieved from biogas production can be profitable for plants able to satisfy a large portion of their energy requirements, so CH_4 emissions reductions from anaerobic digestion projects may not be considered additional. In agriculture, as part of the nitrogen management project protocol, N_2O emissions reductions may only be considered additional if they pass a performance standard test, a legal requirement test, and a credit or payment stacking test.[138]

On the other hand, a study by the U.S. Department of Agriculture on voluntary payment programs suggested that farmers were unlikely to adopt conservation practices, including those that reduce GHG emissions, that were expensive to install or provided only limited on-farm benefits without payments.[153] Accordingly, such practices could satisfy the conditions for additionality.

Avoiding baseline inflation

Baseline emissions are those that occur, or would occur, without implementation of a specific management activity. This baseline is used to quantify the expected emissions reduction associated with the activity.

Baseline inflation describes a situation in which the baseline emissions used to quantify a reduction are higher than actual current or expected sector emissions. As a consequence, the emissions reduction potential and carbon credit value of an activity will be overestimated. Baseline inflation causes overvaluation of mitigation activities and inefficient markets.

Issues with quantifying both CH_4 and N_2O emissions baselines are driven by data collection needs in most sectors. As an example, determining CH_4 emission leakage rates from the oil and gas sectors has been an ongoing challenge because of difficulties associated with data collection. There are two methods for estimating CH_4 leakage rates from oil and gas operation: unit process level measurements that are extrapolated to entire equipment populations and aircraft-based emissions measurements of regions where oil and gas is extracted. The range of reported CH_4 leakage rates is 1.2%–1.4% of the total CH_4 production.[32] Choosing a baseline emissions value for this sector therefore requires choosing which value in this range is most defensible. As more data continue to be collected from this sector, emissions estimates and therefore baseline setting will improve.[36] Currently, in oil and gas CDM projects, baseline emissions are typically based on site-specific measurements of CH_4 leaks before repair, which is best practice. However, some projects calculate leakage rates instead of making direct measurements, which could result in erroneous baseline estimates.[154] Inflated baseline challenges also exist in the coal sector. One challenge in setting a baseline for CH_4 emissions from abandoned coal mines is that emissions fluctuate depending on the extent of flooding, which lowers emissions. If flooding is ignored in baseline setting, the corresponding baseline emissions may be too high. In the agricultural sector, N_2O emissions are highly dependent on soil type, precipitation rates, and fertilization types and amounts. Recent work has also shown that field N_2O fluxes can vary diurnally, and the factors driving these variations are not well understood.[155] Accordingly, accurate baselines for soil N_2O emissions can be challenging to determine.

Avoiding perverse incentives

When the carbon credit value of a management activity makes an industry more profitable, this monetary incentive may promote industry growth such that overall emissions remain the same or even increase compared to what would have occurred without the carbon market existing. The underlying, credit-based mechanism for this outcome is called a perverse incentive. One example of this phenomenon arose upon adoption of the Rice Cultivation Protocol adopted by CARB in 2015. The protocol provides an additional income opportunity for rice projects that adopt specific eligible practices to reduce CH_4 emissions. It provides offsets for reduced CH_4 emissions, which translate to economic benefits under the cap-and-trade program. Such economic benefits can tilt the scales of profitability toward rice cultivation compared to other crops. As a result, farmers in the Mid-South United States and in California, responsible for most of the rice cultivation in the U.S., could switch to rice cultivation from corn cultivation.[156] This could lead to greater emissions from the agriculture sector because rice is more GHG intensive than corn.[157] However, the impacts of changes like this should be assessed for an expanded system that enables consideration of potential reductions in rice production elsewhere or changes in systems that use corn, like livestock production, that could offset emissions increases related to switching from corn to rice.

Perverse incentives can also arise in other sectors. For example, there is concern that providing carbon market incentives for CMM capture could make coal mining more profitable, resulting in an actual increase in CH_4 emissions due to increased coal production.[158] We have also mentioned the 45Q tax credit in the U.S. (see the "non-CO_2 provisions in global carbon markets" section). This credit incentivizes CO_2 capture in activities such as natural gas power plants. CH_4 emissions could increase as a result of the energy penalty of CO_2 capture, that would require an increased supply and extraction of natural gas.

Temporal variation of carbon prices

Incentivizing the mitigation of non-CO_2 gases requires a detailed understanding of the temporal assumptions that set a market price. Conventional market prices and technology costs are often reported in US dollars per tonne of CO_2 equivalents. Here, both the carbon price in the numerator and the quantity of emissions in the denominator vary with time.

In the case of the carbon price, the climate policy literature indicates that carbon prices would need to increase by more than order of magnitude over the next eight decades for meeting the 1.5°C/2°C Paris Accord targets.[159] For instance, the High-Level Commission on Carbon Prices arrived at a consensus carbon price of \$40/t-CO_2e in 2020, \$80/t-CO_2e in 2030, \$200/t-CO_2e in 2050, and almost a \$1000/t-CO_2e in

2100.[160] These projections assume that technology costs will substantially decline so that these carbon prices are achievable.[159] However, there are several issues with such a pricing trajectory. For instance, this approach does not incentivize many off-the-shelf technology options that cost \$50–100/t-CO_2e today. It does not achieve mitigation of relatively easy-to-mitigate emissions in the next two decades during which the global temperature rise would exceed 1.5°C.[161] Subsequently, carbon dioxide removal would be needed to bring down temperatures to the 1.5°C constraint. Hence, other pricing strategies have been suggested. For instance, Strefler et al.[162] suggest carbon prices should increase to \$100/t-CO_2e by 2030 and stagnate at about \$400/t-CO_2e in 2100. They argue this approach would reduce the harmful impacts of failing to achieve emissions reductions targets and the corresponding temperature rise. Notably, the cost of mitigation for a broad range of emissions is in the \$50–100/t-CO_2e range, which indicates this approach may be viable. Another benefit of this approach is its general stability, which could also garner more public support than approaches that abruptly increase carbon prices.[163]

Accounting for varying lifetimes of non-CO_2 gases

The cost of per ton CO_2e removed is also influenced by the lifetime of non-CO_2 gases. The CO_2-equivalent GWPs of CH_4 and N_2O are both time dependent because their atmospheric lifetimes are very different from the lifetime of CO_2, which is between 300 and 1000 years. CH_4 has a lifetime of 11.8 years and exerts a very high radiative forcing in the short term, with a GWP_{20} (20-year time horizon) of 79.7 and 82.5 for non-fossil and fossil sources, respectively. However, its GWP_{100} (100-year time horizon) for non-fossil and fossil CH_4 are 27 and 29.8, respectively. Thus, if CH_4 levels were to suddenly fall to near-zero due to aggressive mitigation, its concentration would also decrease to zero in some decades, inducing a "global cooling" effect.[164] On the other hand, N_2O has a longer lifetime, 109 years. As such, while an immediate reduction in emissions would reduce any additional increase in its atmospheric concentration, more than a century would still be required for its concentration to start decreasing. Thus, no "global cooling" will be seen in the interim from rapid N_2O reductions. The differing behaviors of these gases mean that immediate CH_4 reductions are important to limit the risk of overshooting emissions reductions targets.

Although GWPs are the most common metric used to evaluate non-CO_2 GHG emissions, they do not address temporal factors that are critical for short-lived climate forcers like CH_4. Other metrics do address these effects.[165] For instance, the technology warming potential[166] considers the continuous accumulation of GHG emissions in the atmosphere and the associated radiative forcing over time. Its dynamic treatment of emissions permits quantification of realistic time tradeoffs of implementing mitigation efforts that reduce emissions of different GHGs.[167] We recommend consideration of such metrics in evaluation and development of market mechanisms to reduce CH_4 and N_2O emissions. For instance, if a 100-year time horizon is applied to CH_4 control technologies in 2050, it would under-incentivize CH_4 emissions mitigation.

CONCLUSIONS AND OUTLOOK

If we are to meet global targets for climate change mitigation, decisive action must be taken to incentivize reductions in CH_4 and N_2O emissions. Although CH_4 and N_2O are emitted in lower quantities than CO_2, their warming potentials are high. To keep global temperature increase below 1.5°C, median CH_4 emissions must decrease by 34% in the next decade and by 50% by 2050, and median N_2O emissions must decrease by 11% in the next decade and by 25% from 2035 to 2050[15,159] (Figure 2).

Encouragingly, as we have reviewed in section on "sectoral emissions mitigation", strategies exist to mitigate emissions in all the key sectors. Additionally, most CH_4 and N_2O emissions reduction strategies are either profitable or could be easily incentivized with inclusion in carbon markets. In fact, nearly all CH_4 emissions can be mitigated for under \$50/t-CO2e, and about 30% can be mitigated at profit. Despite the need to reduce emissions, the availability of mitigation technologies, and the low costs of most strategies, prominent carbon markets (reviewed in "non-CO_2 provisions in global carbon markets") exclude CH_4, N_2O, or both. As reviewed in the section on "challenges with impact assessment and pricing", appropriate incentivization of mitigation strategies will require that markets have protocols in place to ensure additionality, estimate baseline emissions consistently and accurately, and avoid perverse incentives. Currently, many existing market-mechanisms do not ensure that emissions are additional. Temporal variations in carbon prices and in the warming potentials of emitted GHGs could also influence the effectiveness of carbon markets. For instance, if a 100-year time horizon is applied to any CH_4 control technologies in 2050, these technologies will be under-incentivized in consideration of near-term warming mitigation goals. Thus, evolving market frameworks need to account for the dynamic GWPs of CH_4 and N_2O, especially as more markets continue to bring them within their coverage.

An obvious question is whether it is possible to achieve the required emissions reductions to meet the aims of the Paris Accord. Certainly, ongoing emissions reduction technology development will continue to play a role. Yet, the answer may hinge on whether emissions mitigation activities are incentivized in carbon markets in a way that effectively deals with additionality, baseline inflation, perverse incentives, and short-lived climate forcers like CH_4.

Limitations of the study

There are three key limitations to the scope of this review. First, the data reported in this paper rely on existing datasets and inventories of CH_4 and N_2O emission and mitigation. These underlying values are themselves subject to wide uncertainty due to measurement and methodological ambiguities. Second, the review discusses global and U.S.-level trends in mitigation. Individual national and state governments are likely to prioritize mitigation in individual sectors based on their regional context. As such, our recommendations do not apply uniformly to all regions. Finally, key conclusions from this review on the cost of mitigation being cheaper than the current available carbon price assume a static time-dimension and do not account for market inertia.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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